Universal Frequency Domain Baseband Receiver Structure for Future Military Software Defined Radios

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Future military waveforms are most probably implemented on software defined radios capable to handle several waveforms. Implementation of several waveforms would require design of several receiver chains. In order to ease these design tasks, this paper describes a universal frequency domain baseband receiver structure. The structure may be used as a starting point to design receiver basebands for different waveforms, which simplifies the design process. Indeed, the design issue is reduced to plan the contents of different building blocks. The paper explains how the structure should be used for multicarrier and single carrier signal demodulation, fast synchronization even with large carrier frequency offset, channel estimation, interference cancellation and spectrum sensing as well as briefly discusses the possible contents of blocks.

Keywords: Uniform receiver architecture.

INTRODUCTION

Future military radios most probably need to handle several waveforms that may be based on single or multi carrier modulation technologies. Therefore, software defined radio (SDR) is the most probable platform. In addition to demodulation the receiver is asked to perform fast synchronization, efficient channel estimation and equalization. Furthermore, future cognitive properties ask for spectrum sensing as well to recognize free and used frequency slots. This variety of different techniques and tasks sets high demands for receiver designers.

Recently, it has been more widely recognized that a frequency domain receiver could be used to receipt single carrier (SC) and multicarrier (MC) signals very efficiently since it uses computationally simple frequency domain filtering techniques. This trend is mainly a consequence of future civilian wireless standards like LTE which uses multicarrier modulation in downlink and single carrier modulation in uplink [1].

In addition to demodulation and related functions such as frequency domain channel estimation and equalization, which are usually considered in the literature, the receiver also has to perform synchronization. In some cases frequency uncertainty is large such that also coarse frequency search has to be executed together with symbol timing. This occurs with high mobility especially if this is combined with low signal energy such that long detection intervals are needed. This is the case in Global Positioning System (GPS) or other satellite navigation systems that are clearly candidate waveforms for future soldier radios, but also in wireless communications when low quality clocks and low data rates (robust modes) are considered.

Future cognitive radios need to detect free frequency slots and need spectrum sensing for that. Since the spectrum sensing is often done in the frequency domain it naturally falls to the concept of frequency domain (FD) receiver. There is also a small step from spectrum sensing to narrowband interference detection and mitigation, i.e., notch filtering.

This paper offers the generic FD baseband receiver structure and explains its use for SC and MC demodulation with FD channel estimation and equalization including iterative receivers. There are signals

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14. ABSTRACT
Future military waveforms are most probably implemented on software defined radios capable to handle several waveforms. Implementation of several waveforms would require design of several receiver chains. In order to ease these design tasks, this paper describes a universal frequency domain baseband receiver structure. The structure may be used as a starting point to design receiver basebands for different waveforms, which simplifies the design process. Indeed, the design issue is reduced to plan the contents of different building blocks. The paper explains how the structure should be used for multicarrier and single carrier signal demodulation, fast synchronization even with large carrier frequency offset, channel estimation, interference cancellation and spectrum sensing as well as briefly discusses the possible contents of blocks.

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with and without guard intervals between symbol blocks (e.g., cyclic prefixes) [1]. Since these require different FD processing that aspect is addressed as well. The just mentioned aspects are more or less well known. Therefore, the paper puts more emphasis on more unfamiliar aspects and explains FD synchronization even with large frequency offsets as well as integration of spectrum sensing and notch filtering as a part of the receiver.

The aim of the paper is to provide an overview of the universal FD baseband receiver structure and its use. It is hoped that this eases receiver designers' tasks when they design multiwaveform platforms.

RECEIVER STRUCTURE

The proposed receiver structure is shown in Fig. 1. It contains all the blocks needed in the most generic form. Some forms may not need all the blocks and unnecessary blocks are just bypassed. The contents of the blocks naturally depend on the task, e.g., demodulation and synchronization. In what follows the block contents are briefly explained first in general and then for specific waveforms and tasks.

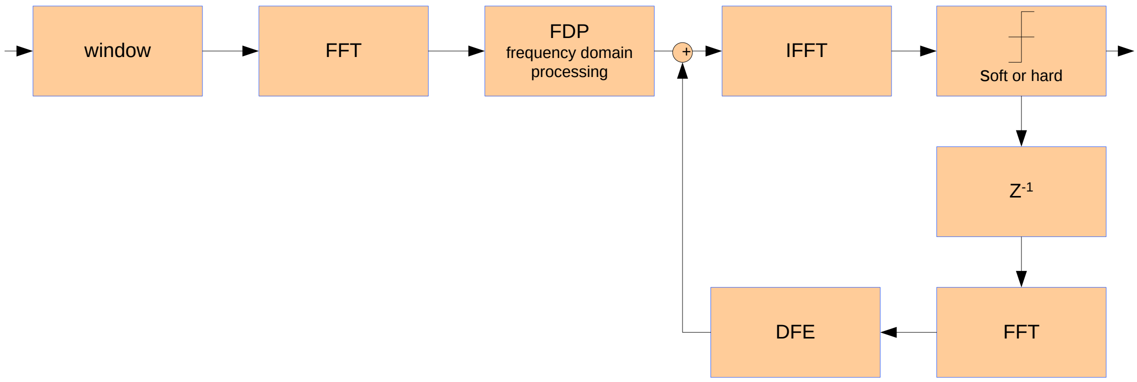


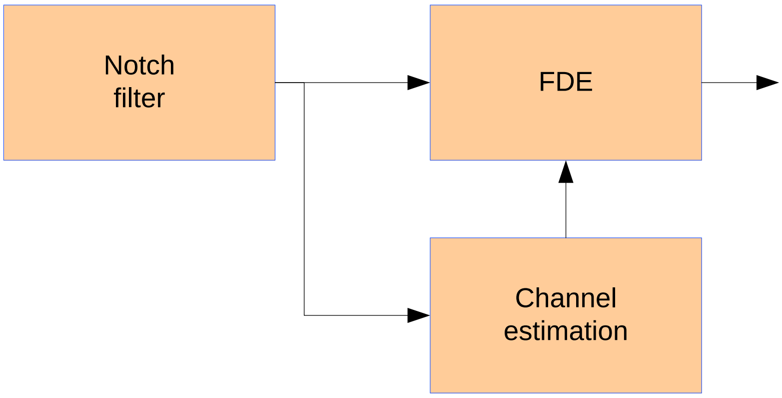
Figure 1: The Proposed FD Receiver Structure.

Some readers may be more familiar with traditional SC processing where symbols are treated in a serial manner. The proposed structure differs from that since it treads signals in blocks. This means that it takes a block of samples in and spits out a block of symbol decision variables, i.e, it treads several samples (symbols) at the same time.

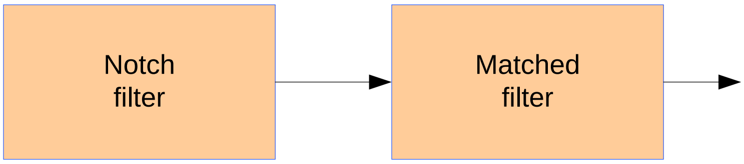
The window block in Fig. 1 is used to remove the guard interval (e.g., cyclic prefix). It can be used also to reduce spectrum leakage effect on spectrum sensing and notch filtering. It is indeed essential for the proper performance of notch filters [2].

The fast Fourier transform (FFT) block brings the signal to the frequency domain. The FFT size should be variable to cover different waveforms and tasks since demodulation and synchronization phases may require different FFT size as will be seen.

The frequency domain processing (FDP) block does required FD tasks like channel estimation, equalization, FD multiplication by filter coefficients, spectrum estimation, notch filtering, etc. Obviously, this block may include several consecutive tasks as illustrated in Fig 2. Fig. 2a shows typical demodulation construction if notch filtering is included together with channel estimation and frequency domain equalization (FDE). Fig. 2b shows construction for synchronization. Therein, the FD matched filtering approach is applied, i.e., FDP is equal to element wise (frequency bin wise) multiplication by the reference signal's FFT.



a)



b)

Figure 2: Possible Contents of FDP Block.

The included symbol blocks separator (guard) allows using the circular convolution principle. In practice this means that the FFT size needs to be equal to the block size, e.g., the number of subcarriers in MC modulation. If the separator is not used (like in traditional SC systems or GPS), then the overlap-add or overlap-save methods have to be used for proper FD filtering. In practice this means that the FFT size must be larger than the block size. Let N be the block size and M the filter size. Then the convolution length is N+M-1 and that is the minimum size for the FFT. In practice, the FFT size is the next power of two of this number. This increased FFT size is the penalty of not using the separator. The benefit is increased throughput since the separator does not waste capacity [1]. The performance (with respect to signal-to-noise ratio (SNR)) should be similar in both the cases. The overlap-add or overlap-save methods are also needed in the synchronization phase that requires continuous filtering by the reference signal until the signal is found (detected).

One advantage of FD receiver over time domain (TD) correspondence is that the equalizer length is usually quite large since it is quite economical to compute a long FFT. This means that the equalizer covers several delay spreads at the same time. It covers short delay spreads (order of 2 µs) encountered in urban environment as well as long delay spreads (order of 20 µs) encountered in hilly and mountain areas. This is clearly an advantage in military systems that should function in urban, hilly as well as flat desert areas. The separator systems do not have this benefit since on those the separator must handle the delay spread. A drawback is increased complexity since the FD equalizer (both FDE and DFE) are longer than necessary. However, the overall complexity and flexibility are what clinches. An example of needed FFT length follows. Let the symbol rate be 10 Msymbols/s. Then 20 µs is covered by 200 symbol samples, which is rather short for even today's real time FFT processing at given sample rate. On the other hand, corresponding 200 taps TD equalizer filter is still quite a challenge at high sample rates.

If demodulation or other detection (like that in synchronization) is performed in the time domain (TD), the inverse FFT (IFFT) block is needed to bring the signal to the correct domain.

It is well known that operation on frequency selective channels may require iterative reception, especially in SC modulation. The decision feedback equalizer (DFE) is a well-known iterative solution where previous decisions are utilized for improved performance. More modern approach (and computationally demanding) is the iterative approach where the delay (z^{-1}) block is omitted. During the iteration (or feedback) both the linear feedforward (FDE) and feedback (DFE) parts are usually updated. Some rules for the iterative receiver are given in [1, 3].

At the multicarrier systems natural sampling rate to the proposed chain equals system bandwidth, i.e., the block size equals the number of subcarriers. This is called one sample per symbol case corresponding to the single carrier situation. However, in the synchronization phase oversampling is usually required to better align proper timing instant. In this case processing could still be done one sample per symbol rate but that is repeated by the oversampling rate. This holds also for synchronization in the single carrier case. In demodulation in the single carrier systems processing could be one sample or multiple samples per symbol based. The latter is called the fractional equalizer case.

Multicarrier Demodulation

MC demodulation requires only the window, FFT, FDP and detection blocks, but could also adopt the iterative receiver (without the internal (I)FFT blocks). The channel estimation is done in the FD based on preamble or pilots. Averaging over some nearby pilots may be used for improved estimation performance, but, on the other hand, averaging over a large or the whole band is not sensible on frequency selective channels since the channel response includes phase changes and fades. The simplest FDE is the channel matched filter (CMF). Let C(f) be the channel and X(f) its estimate based on pilots. The CMF R(f) = X*(f). Let Y(f) = C(f) S(f) + N(f) be the received FD signal where S and N denote the data and noise, respectively. The output of the equalizer is X*(f)C(f)S(f) + X*(f)N(f). Clearly, with a good channel estimate, this is the optimal receiver and also simple since it does not include any divisions that are “nightmares” for implementation. Other FDEs are the zero forcing and minimum means square error (MMSE) equalizers. However, it has been shown that the MMSE equalizer suffers from an error floor at high SNR values in frequency selective channels, i.e., it may have a poor performance at good conditions [4].

Military systems may require a direct sequence (DS) component for additional robustness and also to scale the data rate. In MC world this can be added in the frequency domain, i.e., a symbol is spread over some frequency bins using a spreading code. This is called the MC-CDMA signal. Note that spreading does not need to cover all the subcarriers but just a few, like 4, 8 or 16. Naturally, the required despreading is done in the FD. The FDE could be applied either for chips or despread symbols.

Single Carrier Demodulation

SC demodulator needs all the blocks, except if the separator is not used in which case the window block could be omitted if not needed for other reasons like spectrum sensing. The FD channel estimation and equalization are done exactly as in the MC case. Now the pilots are the FFT of the preamble and this may not always be the best selection since there might be very low energy frequency bins. It should be wise to look for preambles with appropriate frequency domain properties.

A DS component can be added as usually. The FDP block then includes this code as a reference (matched filter). If d(t) is the spreading code, the FDP includes multiplication by its FFT D*(f). After the IFFT, one should sample from the correct position since the receiver results in full correlation as illustrated in Fig. 3. An alternative is to do FD despreading as in MC-CDMA. Some systems may include long codes (usually also low data rates) or scrambling codes. A long code may include several symbols as well at higher data

rates. FFT processors may not support such a large FFT sizes. In that case FD block processing may be applied [5]. It allows division of a long filter into smaller blocks, i.e., a smaller FFT size is sufficient. This is considered more detailed in the section that considers synchronization. Scrambling yields time varying filters since trivial multiply by scrambling chips before usual receiver operation is not the best solution on multipath channels. This means that one has to update the scrambling code content of the reference in the FDP block for each incoming signal block, which increases complexity since FFT is required for all scrambling code blocks.

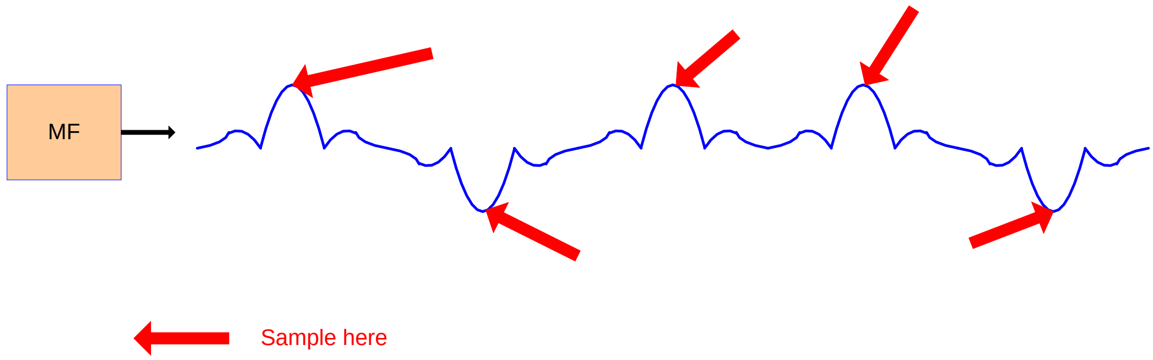


Figure 3: Output Example in DS Component Case.

SYNCHRONIZATION

Frequency domain synchronization and block filtering are less familiar such that these concepts are explained herein more detailed. A good information source is [5] and references therein. Let s(t) be the preamble used for synchronization and S(f) its FFT. Note that this covers both the MC and SC cases. In the MC case s(t) is after the IFFT of the transmitter. Let $Y(f) = C(f)\ S(f) + N(f)$ be the received FD signal where C and N denote the channel and noise, respectively. In the additive white Gaussian noise (AWGN) channel the optimal receiver computes the energy of $S^*(f)Y(f)$ and compares that with a detection threshold to decide was the signal present or not. This computation can be done either using the correlation or the matched filtering principle, of which the latter yields much faster synchronization times and is a preferred choice for military systems. Luckily, the matched filter (MF) can be implemented efficiently using the FD receiver structure without feedback. The overlap-add (or overlap-save) method has to be used. The results is like a single peak in Fig. 3 if sole preamble is send and a series of peaks if repeated preamble is used for increased sensitivity (instead of one long preamble). The peaks are combined either coherently (on AWGN channels) or non-coherently if phase changes make the coherent combining impractical. Also large carrier frequency offset (CFO) may make the coherent combination impractical. CFO may even make integration over a minimum required interval impractical. In that case joint frequency and timing synchronization has to be performed. This is considered next. Special cases of this are the usual non-block systems and systems without CFO estimation.

Let the filter length be N and it is divided into parts of length M. The parts are called partial matched filters (PMFs). The PMF outputs are fed to the FFT calculation of size N' resulting in an N×N' block in the delay-frequency search matrix. The concept is illustrated in Fig. 4. One looks for threshold crossings in the matrix to detect the presence of a signal.

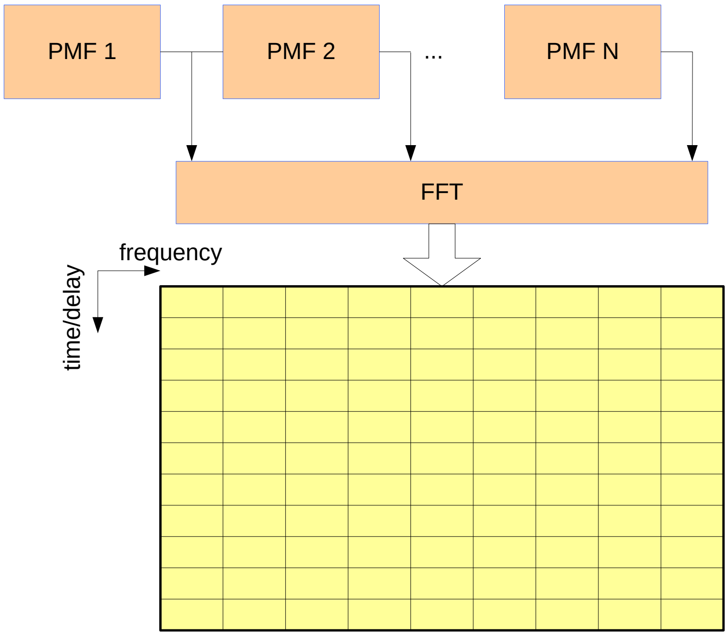


Figure 4: Concept for Joint Timing-Frequency Synchronization Using Block Filtering.

This concept can be implemented in the FD as explained in [5] wherein the operation of the system as well as selection of the parameters like block size M and FFT size N' are discussed. An illustration of operation is shown in Fig. 5. Especially it should be observed that overlap-add method is applied between the blocks in order to quarantine proper operation. This means that the FFT size N_{FFT} for input signal blocks is larger (the next power of two) than 2M-1. Second observation is that blocks are multiplied at one time in an element wise matrix multiplication by the corresponding matrix of the FFTs of the filter blocks. A cycle denotes an operation interval where input is taken and processed. In the next cycle, the first M samples (the first block) of the previous state are ignored and a new block is taken in. The output of a cycle contains M samples (or M×N' if CFO estimation is needed). These are at the head (H) part that is the first M samples of the output block of size N_{FFT}. The rest samples belong to the tail part (T) and are a consequence of convolution and handled using the overlap-add method in the figure. This process may also be called short time Fourier transform (STFT) based filtering [5] and the transformed signal and filter matrices as the STFT of the signal and filter, respectively.

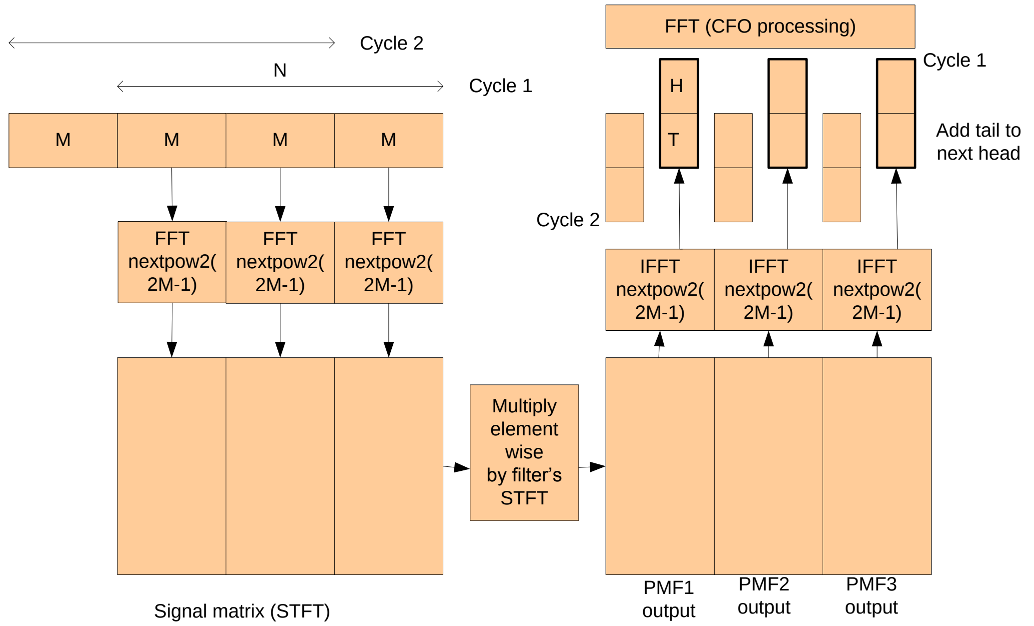


Figure 5: Illustration of Operation of Frequency Domain Block Filtering.

If the FFT processing is ignored after the PMFs, the concept results in the usual FD block filter. If the PMF contents are varied with time, a time varying block filter is obtained. In a special case of a single block the system reduces to the usual FD filter.

In long DS code communications the block size should correspond a symbol such that the outputs of PMFs (in the time domain at the correct moments) give symbol decision variables. It is also possible to include FDE computation inside the blocks. Block filtering is indeed a way (in addition to time varying filtering) to allow long spreading codes which are more difficult to guess by an adversary.

In multipath environment it is important to search all (and especially first) threshold crossings since the largest peak may not be the first one and that would cause problems (bias) in FH timing.

SPECTRUM SENSING AND NOTCH FILTERING

Future cognitive radios need spectrum sensing to detect free and used frequencies and maybe some other detections to recognize existing signals but the latter are out of scope herein. Spectrum sensing typically means FFT and then some averaging. Indeed, temporal windowing is required for better performance like in the Welch spectrum estimator [6]. Therefore, the proposed structure directly fits spectrum sensing. The content of the FDP block then contains the spectrum calculation and signal detection. Note that there might be many signals, especially if the detection bandwidth is wide. In that case, the detection of several even closely spaced signals is required. A tool for this is the LAD algorithm that clusters the detected samples and separates them as different signals if there are reasons to do so [7].

Especially wideband communication may suffer from unintentional or intentional narrowband interference. The former may occur in an overlay case where wideband and narrowband systems operate at the same time at the same frequency band in the same area. Interference mitigation is a tool for resisting the effects of such interference. Notch filters are suitable for this task. They require spectrum sensing, i.e., FFT, interference detection and, thereafter, limitation or nulling of interfered frequency bins. Usually, spectrum sensing is now without averaging due to real time operation but heavy windows are essential for

proper performance [2]. However, such windows cause some (up to 3 dB) performance losses that can be reduced by using parallel (duplicated) processing. Blind automatic means to detect interfered frequency bins are the consecutive mean excision (CME) algorithms [2, 8]. These do not need to know the signal or the noise level and set the detection threshold based on user set desired false detection probability. Increased robustness achieved using these notch filters are considered, e.g., in [2].

CONCLUSIONS

This paper proposed a universal frequency domain baseband receiver chain for SDR implementation. It can be used to demodulate any signal and perform also other required tasks such as synchronization even with large carrier frequency offsets, channel estimation, equalization, spectrum sensing and notch filtering. Therefore, the proposed receiver chain can be used as a sole starting point when the receivers of different waveforms for future (military) SDR platforms are designed. This simplifies designer tasks since they can rely on one starting point instead of many. Basically, they just have to design the block contents and parameters (like the FFT sizes) for different cases. However, the designers must learn how to use the proposed chain in different cases and how different algorithms are used in it. Some hints to this were given in the paper.

The proposed receiver chain has been applied for a while. For example, in [2] it was used for time delay estimation in DS systems together with notch filters. Recently, it has been applied for orthogonal frequency division multiplexing (OFDM) signals in fading multipath channels in [9].

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